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January 25, 2001

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SUBJECT: PATENT DISCLOSURE LETTER
on: Continuous Prediction, Monitoring, and Control of Compressor Health via Detection of Precursors to Rotating Stall and Surge using Kalman Filter based post-processing on Frequency Demodulation of Acoustic Signatures

I. SUMMARY OF IDEA

This letter discloses the invention of a method to continuously monitor the health of an axial compressor in a gas turbine via the detection of precursors to rotating stall and surge using a technique that performs frequency demodulation followed by post-processing using a Kalman filter. Specifically, the method entails real-time monitoring of one or more dominant frequencies in the acoustic spectrum, as measured by dynamic pressure, velocity, force, or vibration sensors. Abnormal variations in these monitored frequencies are flagged by post processing through a Kalman filter and correlated to the underlying compressor operating parameters.

The level and detailed nature of frequency variation for a baseline compressor is known *a priori*, as a function of the underlying compressor operating parameters, which provides a basis of comparison for inferring the health of the compressor of interest. Based on this health indication, a real-time control system issues necessary actions to protect the machine.

II. PROBLEM TO BE SOLVED

[redacted]

The global market for efficient power generation equipment has been expanding at a rapid rate since the mid-1980's; this trend is projected to continue over the next decade. The Gas Turbine Combined-Cycle power plant, consisting of a Gas-Turbine based topping cycle and a Rankine-based bottoming cycle, continues to be the customer's preferred choice in power generation. This is due to the relatively-low plant investment cost, and to the continuously-improving operating efficiency of the Gas Turbine based combined cycle, which combine to minimize the cost of electricity production.

It is well-known that elevated firing temperature is the key element which enables increases in combined cycle efficiency and specific power. It is also well-known that, for a given firing temperature, there is an optimal cycle pressure ratio which maximizes combined-cycle efficiency. This optimal cycle pressure ratio can be theoretically shown to trend higher with increasing firing temperature.

Axial compressors at the heart of industrial Gas Turbines are thus subjected to demands for ever-higher levels of pressure ratio, with the simultaneous goals of minimal parts count, operational simplicity, and low overall cost. Further, the compressor is asked to enable this heightened level of cycle pressure ratio at a compression efficiency that augments the overall cycle efficiency. Lastly, the compressor must perform in an aerodynamically and aero-mechanically stable manner over the wide range in mass flow rate that is associated with the varying power output characteristics of combined cycle operation.

The general requirement which led to this invention was the market need for industrial Gas Turbines of improved combined-cycle efficiency and based on proven technologies for high reliability and availability. The specific problem solved by this invention is the simultaneous need for high cycle pressure ratio commensurate with high efficiency, and ample surge margin through-out the operating range of the compressor. This invention provides a design and operational strategy that provides optimal pressure ratio and surge margin for both the case wherein the Inlet Guide Vanes (IGV's) are tracking along the nominal, full-flow schedule, and wherein the IGV's are closed-down for reduced flow under Power-Turn-Down conditions.

The operating compressor pressure ratio of an industrial Gas Turbine engine is typically set at a pre-specified margin away from the surge/stall boundary, known to those skilled in the art as surge margin or stall margin, to avoid unstable compressor operation. Typical surge/stall margin ranges from 5% to 25%. Uprates on installed base and new products that leverage proven technologies by adhering to existing compressor footprints often require a reduction in the operating surge/stall margin to allow higher pressure ratios. At the heart of these uprates and new products is not only the ability to assess surge/stall margin requirements and corresponding risks of surge but also the

availability of tools to continuously predict and monitor the health of the compressors in field operations. This invention affords a method of compressor health prediction, monitoring, and control that can be leveraged to be acted upon for protecting the compressor from being damaged due to stall and/or surge.

III. PRIOR ART

[redacted])

The conventional approach to monitoring the health of a compressor is to measure the air flow and pressure rise through the machine. A range of values for the pressure rise is selected a priori, beyond which the compressor operation is deemed unhealthy and the machine is shut down. Any such pressure violation can be attributed to a number of causes such as unstable combustion, and rotating stall and surge events on the compressor itself. For the latter two events, the current state-of-the-art is to monitor the magnitude and rate of change of the pressure rise through the compressor. If and when the event occurs, the magnitude of the pressure rise drops sharply and significantly, and an algorithm monitoring this magnitude and its rate of change will acknowledge the event. This conventional approach does not offer prediction capabilities of rotating stall or surge, and does not offer information to the control system to reactively or proactively deal with such events.

IV. OBJECT OF INVENTION

[redacted])

The object of this invention is a method to continuously monitor the health of an axial compressor in a gas turbine using a frequency demodulation technique or device and post-processing the demodulated signal by a Kalman Filter that detects and flags abnormal signatures in the demodulated signal. These signatures are correlated with the underlying compressor operating parameters. Based on this information, a control system then issues necessary action to protect the machine from potential damage caused by such events. The invention described herein offers a method of continuously measuring and monitoring the health of the compressor by comparing the characteristics of the precursors on the compressor of interest against a correlation derived from a baseline machine. The condition of the compressor of interest is inferred from this comparison. Based on the health condition at the particular underlying compressor operating configuration, actions can be taken by the control system to proactively anticipate and mitigate any potential rotating stall and surge events.

V. DESCRIPTION OF INVENTION

The invention consists of the following elements:

1. Sensors around Compressor – At selected stages, pressure and/or velocity sensors located circumferentially around the annulus of the compressor on the casing and/or in the flow are used to sense the pressure/velocity behavior of the flow through the compressor. Alternatively, it is speculated that force and vibration sensors such as accelerometers or piezoelectric devices could be used to acquire the acoustic signature registered by the compressor casing.
2. Real-time Operating System – A real-time operating system is used to record and process data from sensors for precursor detection.
3. Precursor Detection using Frequency Demodulation Algorithm – Sensor data are collected in real-time. When a pre-specified number have been collected, the time series is first band-pass filtered (BPF) so as to reject all frequencies outside a band of a pre-specified width centered on a particular frequency of interest. A frequency that has proven useful is the tip passage frequency, which corresponds to the product of the number of compressor blades in the monitored stage and the rotational rate of the rotor. The output of this band-pass filter is then frequency demodulated (FDM), producing an output signal whose amplitude corresponds to the instantaneous frequency of the input. In the succeeding block, the demodulated signal is smoothed with a low-pass filter (LPF) to reduce the influence of noise on the original measured signal. The resulting signal is then processed using a Kalman Filter. Time-series analysis of this signal yields a dynamic model used by the Kalman filter. The Kalman filter optimally combines the output of the dynamic model and the actual signal to produce a filtered estimate. The difference between the measurement and the filtered estimate, known as innovations is examined. The magnitude of the standard deviation of innovations yields the desired precursor of rotating stall or surge behavior. The described computation repeats in the next servo loop with newly acquired data and the precursors are tracked continuously.
4. Correlation of Precursor Signal Characteristics to Compressor Operating Parameters – the magnitudes of the precursors, i.e., standard deviations of innovations is known from a baseline compressor as a function of the underlying compressor operating parameters, such as pressure ratio, air flow, and/or effectivities. This correlation is derived by analyzing offline data from a prior test vehicle at known operating conditions.
5. Real-Time Control System – If the machine is deemed unhealthy based on the value of the operating parameter inferred from the stall precursors, protective actions are issued by the real-time control system to mitigate risks to the machine.

The operation of these elements is as follows. Data from sensors from around the compressor are sent to the real-time operating/control system. The appropriate signal pre-processing such as filtering is performed to clean the signal. This filtered signal is then stored in memory. When the number of data reaches a pre-determined level, the demodulation is performed on the data. The demodulated & filtered data corresponding to normal operation is used to construct a dynamic model to be used by the Kalman filter. Subsequently, the Kalman filter updates its filtered prediction estimate of the next data sample based on the most recent data sample. The innovations are constructed by taking the difference between the measured value and the filtered estimate. When a

pre-determined number of data points of the innovations are collected, their standard deviation is computed. This magnitude of the standard deviation is then compared to that from the known correlation for the baseline compressor. Based on the difference between these magnitudes, the compressor of interest is then deemed healthy or unhealthy. In the latter case, the real-time operating/control system issues actions on the gas turbine to reduce the loading on the compressor and wait for appropriate actions such as maintenance.

Alternate realization. As an alternative, one or more of the frequency demodulation algorithm and the band-pass and low-pass filtering operations can be implemented using analog circuitry. If demodulation and filtering are implemented this way, the sensor signals are passed directly to the analog circuitry, and the output signal from the circuitry is sampled and stored in place of the raw sensor signals. From this point the extraction of characteristic values from the demodulated and low-pass filtered signal, and the subsequent Kalman filter based processing proceeds as previously described. A significant advantage of an analog realization is a greatly reduced sampling rate for the data acquisition process. This is because the bandwidth of the signal is reduced from order 10 to 10,000 Hz before demodulation to order 10 to 100 Hz afterward. The sampling rate benefit is only realized if both the band-pass filter and frequency demodulator are analog; the low-pass filter can be implemented in a software algorithm on the Real Time Operating System without impacting the sampling rate.

VI. REDUCTION TO PRACTICE

Although the method has not currently been reduced to practice, it is intended to be applied and implemented on the first 7251 FB Gas Turbine.

VII. PLANNED USE OF THE INVENTION

The methods described in this invention are applicable to the full GE Gas Turbine product line.

VIII. RECORDS

This method was developed by joint efforts at CRD-Niskayuna and CRD-Bangalore as part of the Stall Precursor Detection and Control Project. The program started in first quarter of 2000.

IX. WITNESSES AND DATES

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